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ABSTRACT

Investigations of changes in conceptions during physics instruction are the logical and necessary steps to follow successful international research on students' preinstructional conceptions. The theoretical perspective integrates currently available frameworks of cognition, cognitive states, and cognitive processes in physics. Particular emphasis is put on "intermediate conceptions," mainly as a result of students' self-development of cognitive systems. In this case study an individual high school student's learning processes in the domain of quantum atomic physics is investigated. The goal is to elaborate the students' cognitive system for atomic physics as a hypothetical model to describe and explain their thinking and learning interaction with the teaching input. The model serves as a means to explain how and why students act the way they do in a certain instructional context. The students' learning process is described concerning their conception of an atom as a conceptual growth. Their final conception of an atom is a federation of several connected conceptions including their initial planetary model as the point of reference. The conceptions do not exist isolated in their different generating contexts. Students were able to reflect on the differences and advantages of each The student was able to reflect on the differences and advantages of each conception. (Author/PVD)

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Learning pathways in high-school level quantum atomic physics

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ED 406 154

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Abstract

Investigations about changes of conceptions during physics instruction are the logical and necessary step to follow successful international research on students' preinstructional conceptions (e.g. Pfundt & Duit, 1994). Our theoretical perspective integrates currently available frameworks of cognition, cognitive states, and cognitive processes in physics (e.g. Duit, Goldberg & Niedderer, 1992). Particular emphasis is given for "intermediate conceptions", mainly as a result of students' self development of cognitive systems. Our framework presents a new perspective on the development of cognitive systems during teaching, and differentiates between "conceptual change" as forming new additional cognitive structures or changing the qualities of existing structures. Possible qualities used in different studies are "status of a conception", "strength of a conception", "level of explanation", and "level of complexity".

In this case study, we investigate an individual high school students' learning processes in the domain of quantum atomic physics (a regular part of the Grade 13 curriculum for those students that major in physics). Our aim is to elaborate the student's 'cognitive system for atomic physics' as a hypothetical model to describe and explain his thinking and learning in interaction with the 'teaching input'. We don't claim that the mind is biologically or psychologically structured according to our model. The model serves as a means to explain how and why students act the way they do in a certain instructional context. A systematic evaluation of our teaching approach is not the goal of this project.

We describe the student Carl's learning process concerning his conception of an atom as a conceptual growth: His final conception of an atom is a 'federation' of several connected conceptions including his initial planetary model as the point of reference. The conceptions don't exist isolated in their different generating contexts. There is a 'superior administration': Carl is able to reflect on differences and advantages of each conception.

The results are given in more detail in a doctoral dissertation (PETRI 1996).

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1. Introduction

1.1 Starting-point

Compared to other domains of physics there exist only few investigations into students' preconceptions and conceptual change in the domain of quantum and atomic physics already. The most important previous research was done by Bethge (1988) and Lichtfeldt (1992). Both investigated students' preconceptions, but LICHTFELDT (1992) also investigated individual learning processes in quantum physics. He mainly focused on wave-particle problems of free electrons (double slit experiment, uncertainty principle, etc.) with only few general results on atoms. He described learning steps as changes in individual "dynamic networks of ideas". The resulting diagrams show the direction and extent of students' conceptual development, but can't make conceptions explicit or reveal details of the cognitive processes.

1.2. Main research goals

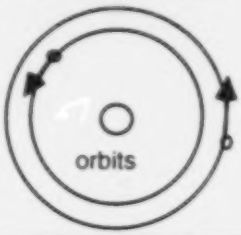
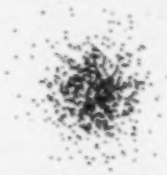
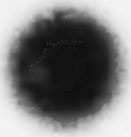
- Starting from a "model of cognitive elements in a cognitive system" (NIEDDERER & SCHECKER 1992, 78) we want to further develop our method of describing learning pathways (SCOTT 1992).
- Covering a 15 weeks-teaching module we want to describe and analyze an individual students' learning pathway as detailed as possible.
- We want to increase knowledge about the cognitive tools students' use especially in atomic and quantum physics (conceptions, epistemological beliefs, etc.).
- We want to investigate the resonance of the "teaching input" on the development of the students' cognitive system.

1.3 Design of the research project

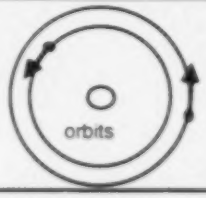
A pilot study (PETRI 1992) was based on a 6-week instruction module developed and taught by H. NIEDDERER. Taking into account the results of the evaluation, we elaborated a modified and enlarged instruction module to be taught and videotaped under similar conditions in autumn/winter 1993/94. The teaching approach is described in Niedderer et al. (1994, 1996). We chose four of ten students to be continuously observed during the entire instruction process that finally lasted 15 weeks (Oct. 93 - Feb. 94). Several interviews, tests and papers elaborated by the students provided additional data. Pre- and long term post-teaching interviews on students' conceptions of electrons and atoms were carried out in May 1993 (during introduction of quantum ideas; natural setting) and May 1994 (laboratory setting), respectively. The results are given in more detail in a doctoral dissertation (PETRI 1996).

2. Carl's learning pathway and details of knowledge construction

Carl's learning pathway can be described with four steps of his conception of the atom:

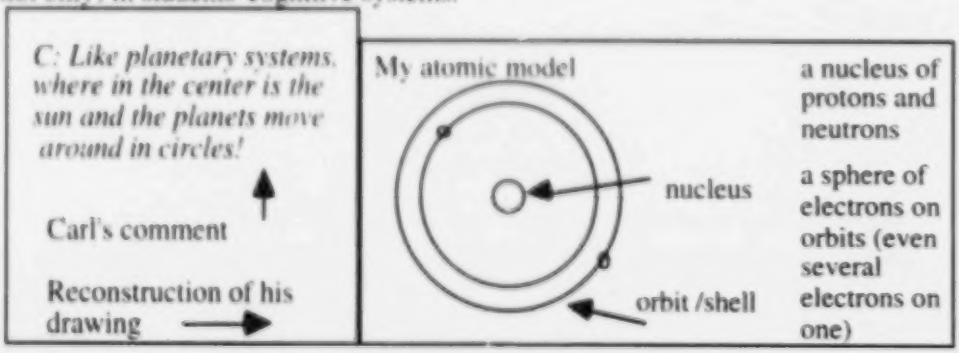
Carl's **first conception C1** ("Planetary model") 	Carl's **second conception C2** ("Probability orbits", "Smeared orbits")
Carl's **third conception C3** ("Quantum model") 	Carl's **fourth conception C4** ("Orbital model", "Electron cloud") 

2.1 Carl's first conception of the atom

	Carl's first conception C1 of the atom: **Planetary model** A nucleus of protons and neutrons is surrounded by electrons in planetary orbits.

Some evidence from the interview carried out five months before the start of our teaching unit

In regard of similar results of BETHGE (1988) and LICHTFELDT (1992) we called the "planetary model" the initial state of the cognitive element "atom", because similar conceptions are found to be deeply anchored (not only) in students' cognitive systems.


C: Like planetary systems, where in the center is the sun and the planets move around in circles!
Carl's comment
Reconstruction of his drawing
My atomic model
nucleus
orbit /shell
a nucleus of protons and neutrons
a sphere of electrons on orbits (even several electrons on one)

Cognitive tools used to construct this prior conception "planetary atom"

Analysing this conception for cognitive tools being used in its construction, we come to the following:

- basic idea 1: an atom consists of a nucleus and electrons around
- basic idea 2 (metaphor): "electron", seen as a "particle"
- language elements being used with these two basic ideas: a particle can move, and by moving around it creates orbits which build up the atom.

This set of tools is similar to a language production system. It can create create a whole set of single ideas

2.2 Carl's second conception of the atom

Teaching input

During a first part of teaching with free electrons, the electron is connected with two new ideas:

- with electron diffraction, a wave conception about electrons is used
- the uncertainty relation with Planck's constant h is introduced

When students after that come back to the model of an atom, they often construct by themselves the following new intermediate conception.

General description of new intermediate conception

	Carl's second conception C2 of the atom: **Probability orbit or smeared orbit model** The nucleus is surrounded by a possibility-field.[1] Shaped like the ψ-function, it spreads out from the nucleus into every direction. The areas, where ψ has maxima (minima) define the electron orbits.

Some evidence from the second week of instruction

C: If I take the nucleus and think of a field around, a wave-like possibility-field, then, at the moment, I think of drawing a ψ-function as a wave that spreads out equally in all directions. And everywhere, where the probability is higher, there is an orbit. I don't know, I can't get rid of these orbits, though I don't know, where I got them.

Hypothetical cognitive tools and teaching input used for knowledge construction

The main theoretical idea is: there are some basic cognitive elements like schema or p-prims or elements of language, which are used by the learner to cope with situations, using these basic cognitive elements as cognitive tools together with features of the situative context to construct there ideas. The main tool here is the notion of a "particle", with the relation "electron as a particle". This immediately gives access to ideas like movement, orbit, mass, charge. It helps students to use tentatively a big number of elements of

[1] The teacher interprets the ψ-function as a possibility-field: the possibility to localize the electron inside the field.

ordinary language to start thinking of these electrons around an atom. Even physicists prefer to use this "particle" view of electron, even if they know it is not correct, because it is so simple and powerful.
Now the new informations of "wave" or "uncertainty" are taken as <u>additional</u> cognitive tools. Combining these tools with the context "nucleus and electron shell" directly leads to the intermediate conception we described above.
This conception is a mixture of several special propositions, which are all of the same type, combining particle and orbit with some new idea related to wave or uncertainty. Three are shown in the following table:

a wave orbit	a smeared orbit	a sample of neighbour orbits with high probability

Cognitive tools	Teaching input
• an atom consists of nucleus and electrons • "electron", seen as a "particle" • a **particle** can move, and by moving around it creates orbits which build up the atom.	• a **wave** conception about electrons is used with electron diffraction • the **uncertainty** relation with Planck's constant h is introduced

<u>Learning as a process of self development of students' cognitive system</u>

We see learning as a complex process depending on both the students' cognitive tools already being there in students' mind and the teaching input, as a process of self development of the cognitive system (Aufschnaiter 1991), being triggered by the teaching input. The cognitive results of instruction can be very different from the teacher's intentions. The new intermediate conception "smeared orbits" is an example for both of these claims. This intermediate conception was <u>not</u> intended or even used by the teacher.

<u>Cognitive attractors</u>

We call intermediate conceptions like "smeared orbits" or "probability orbits" cognitive attractors. To a certain extend, the outcomes of instruction are independend of the special instructional approach. Different instruction can lead to similar cognitive results, in this study described as intermediate conceptions. If similar intermediate conceptions occur in different instructional approaches gives further evidence for self development of the cognitive system: Conceptions similar to smeared orbits or probability orbits have been observed by several authors (Bayer 1986, Bethge 1988, Petri 1996).

2.3 Carl's third conception of the atom

C3: The quantum model	The nucleus is surrounded by a possibility-field. Shaped like the ψ-function, it spreads out from the nucleus into every direction (three dimensional). Inside that field, which is not real, is the "state electron". Because the electron is a quantum object, it is a "state electron", wherein its charge must be somehow distributed. Only when localized, it appears as a real electron. There is no more electron movement.

Some evidence from the sixth week of instruction

C: *Anyway there ain't no electrons moving around in circles anymore ... no real particles that are particles at every moment!*

... We always said it's a state, a quantum object. But partly we speak of electrons again! ... The electron expresses itself only, if you want to ... localize it ... It may be that field ...

C: *You can only speak of an electron, if you get it really localized. ... Yet if you just think of the state of the atom, then the state of the electron, so to speak, is around the nucleus. Somewhere it is, this state that you can force to sometimes appear as an electron. ... I mean, somehow the charge must be there, even if the electron just has not been localized. The charge must be somehow distributed inside that "state electron" or inside this possibility field. ... The ψ-function actually is just a mathematical description of that field, nothing real. But I imagine it's a radial field that points to every direction.*

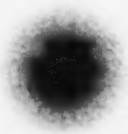
This is Carl's version of the Born's interpretation of the ψ - function. The electron still is a particle when it is localized. But if it is not localized it is a "state electron", this expression was invented by some students, but never used by the teacher.

The following table tries to understand elements of the new conception as cognitive constructions, being a result of interaction between teaching input and cognitive tools in students' mind.

Cognitive tools	Elements of conception	Teaching input
- particle, with mass, charge - <u>not</u> a particle, something new	- electron as a particle, if localized - electron as a "state electron" if not localized	- localisation - the Ψ - function describes states of the atom

2.4 Carl's fourth conception of the atom

	C4: Orbital model, electron cloud model The sphere of the atom, the electron is a smeared charge cloud. The shape of the cloud is that of the orbital(s) and so changes from state to state. The electron doesn't move anymore, it is no particle.



Some evidence from the interview carried out at the end of instruction

JP: *Tom imagined the electron moving to and fro (inside a potential well). How about you?*

C: *That's not my view, because the electron isn't that particle anymore. Meanwhile I withdrew from (that view). ...*

C: *Here in most cases helps this -- smeared electron cloud. There ain't three electrons, but something whole and smeared that can pass into another (state).*

Some evidence from the interview carried out three months later:

C: *Finally I didn't accept any movement of the electron at all, but just assumed it to be there. And it is no longer that electron, that ball, but something smeared, an energy or whatever.*

The effect of teaching described as "resonance" or "non-resonance" - learning processes and knowledge construction

It seems like the new model (being favoured by the teacher anyway) is accepted by the student when he is able to explain the screening effect of electrons in higher atoms (with more than one electron) on the potential around the nucleus. The idea of screening and the idea of an electron cloud seem to be in resonance, helping the student to switch from the cognitive tool "particle" to a new cognitive tool more like "fluid".

Transcript out of the teaching process	**Comment on resonance**
Teacher: How do you understand these two expressions "probability density" and "charge density"? *C: Well, the charge density I see more as a kind of cloud round the nucleus, ther is something real. But a probability density only tells us that, maybe there is an electron, perhaps.* *T: ...can be localized.* *C: ... or being localized. But it does not tell us, that there is something everywhere! Well, the charge density ...* *P: With charge density, there is somethig there all the time.*	The charge density model (C4) helps to explain the effect, that the force of the nucleus on a new electron is screened (reduced) by the smeared electron charge of electrons being already there. This reinforces the conception C4

Transcript out of the interview at the end of teaching	**Comment on resonance**
Int: Do other advantages come into your mind? *C: ... Earlier in grade 9 and 10 in chemistry I did not understand when an electron is belonging to both nuclei in a molecule. ... this can be explained with the orbital model really good. Especially this overlap of the two: it is no more two atoms, besides each other, but one system with a real connection. And we even can calculte this.*	The electron charge cloud helps understanding a molecule and this reinforces the conception C4

3. The final state of Carl's cognitive element "atom"

Different cognitive elements and their "strength" and "status" in final state of cognitive system

We can describe the final state of Carl's cognitive element atom as a "federation" of the first, third and forth conception C1, C3 and C4. To speak of a "federation" means: Several conceptions are connected, they don't exist isolated in their different generating contexts. There is a "superior administration". Carl is able to reflect on differences, problems and advantages of each model. From a lot of qualitative evidence from transcripts during teaching and several interviews we infer: The most powerful conception still may be the first conception, the planetary model of the atom. We say this conception has the highest strength in the fial state of the cognitive system. It will first "raise its voice". But the prestige and influence - the status - of the fourth conception, the orbital or electron cloud model, is higher. This is shown in the following table:

Strength	Status
C1 > C3 ≈ C4	C4 > C3 > C1

When Carl quotes:

> *C: Bohr's model I could even explain to my sister. She is 12 ... but concerning the quantum model she would say: You 're crazy! ...*

this is an excellent demonstration that he has both models in mind. In his mind are several - at least two - layers. This result is similar to that of SCOTT (1992, 222)

Some evidence from a dialog of two students during teaching

In a group work, at the last part of teaching, two students are discussing the H_2^+ molecule. Carl is drawing two nuclei and two ψ-functions. Here, they typically start with electron as a particle and movement in orbits, but lateron change - without external input - to an electron cloud model of the molecule.

Transcript out of the teaching process	Federation of Conceptions
C: This means that the charge cloud from one nucleus comes into interaction with the other!	C4
T: You mean, the electron, only one, is in fact at both nuclei!	C1
C: Yes	C1
T: That means, the velocity in the middle of both nuclei must be nearly zero!	C1
C: Nearly, but not totally!	C1
T: O yes, here (makes noise like moving electrons) *could move between the two nuclei!*	C1
C: Yes, well, I don't imagine the electron as (makes a noise of moving electron and makes movement with hands)	C4
T: But this cloud is able to move!	?
C: No, this cloud does'nt move. Imagine a charge cloud! In this cloud the whole energy, the whole charge of the electron is spread out.	C4

Some evidence from the interview carried out at the end of the instruction

Transcript out of interview at end of teaching	Federation of Conceptions
C: *Anyway Bohr's model is easier to understand. The orbital model ... is a very complex thing that one can hardly imagine. It's just Bohr's model that one can grasp. It is like (something) one can imagine. Because in my world ... the table stands where it stands, it's not a question of probability. I think that's why many people find it really hard - meanwhile I don't that much - to imagine a quantum model of the atom. ... Although the orbital model can of course explain many things in a wonderful manner. And apparently even better, especially energy levels and spectra! It sounds also logical to me, but if I have no imagination of those quanta, I can forget it! Bohr's model I could even explain to my sister. She is 12 ... but concerning the quantum model she would say: You 're crazy! ....*	C1 easy C4 complex C4 C1 and C4

Some evidence from the interview carried out three months later

We anlyse one statement out of the late interview, three month after the end of teaching:

Transcript out of interview three months later	Federation of Conceptions
JP: *Please comment on the following statement: According to the orbital model the electrons don't move on circles and ellipses (Bohr) but inside their orbitals.*	
C: *That's -- the conception before and after! The trajectories ain't that certain circles or ellipses. You don't always know exactly where it is, you only know, where it may be and with what probability. And in an orbital, if you think of a cone, you can see, that it actually can't always move in circles, if you accept a movement at all. Finally I didn't accept any movement of the electron at all, but just assumed it to be there. And it is no longer that electron, that ball, but something smeared, an energy or whatever. It just offers the biggest difficulties to explain to myself, what such an electron actually is. Sometimes, when localized, it behaves like a tiny particle, but when not being localized it's even no particle!*	Talking of layers. Not C1 C3 Not C1 C4 C3, C4

Here, Carl himself - after this long time from the end of teaching - demonstrates his different layers.

4. Some conclusions

- Four conceptions were found to be at least "meta stable" in a learning pathway of one student, thus giving a basis for analysing teaching and learning.
- Some evidence has been given how to explain knowledge construction as an interrelation of cognitive tools interacting with teaching input. Thus an intermediate conception "smeared orbits", which was not intended by the teacher, could be explained.
- Other studies have found the same intermediate conception, so it might well be a candidate for a "cognitive attractor", being constructed by students independent of the special type of teaching.
- Some evidence has been given for resonance of teaching input with cognitive system of the student, thus leading to a conceptual change from a probability model (C3) to a electron cloud model (C4).

- Finally, we gave some evidence for the structure of the cognitive system after teaching: we believe it can best be described as a federation of several coexisting conceptions, or as different layers.

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